Dawn's Second and Final Extended Mission: A New Operational Campaign at Ceres

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Dawn has been in orbit around Ceres since March 2015. In 2016, Dawn completed its prime mission of exploring Vesta and Ceres, and it completed an extended mission at the dwarf planet in 2017. The spacecraft has lost all reaction wheel control, making attitude control dependent on a dwindling supply of hydrazine. Nevertheless, in 2017 the project was approved for a second and final extended mission at Ceres. Starting in April 2018, Dawn used its ion propulsion system to maneuver to two new orbits. These highly elliptical orbits provided hydrazine-efficient opportunities for the acquisition of valuable new data. Now in the second of these orbits, Dawn's lowest altitude is only 9% of the lowest altitude previously in the mission, enabling significant improvements in the spatial resolution of the data. We describe Dawn operations in its second extended mission, the nature of the orbits, and the observation campaigns. We also summarize expectations for the end of the mission.

INTRODUCTION

The Dawn mission was designed to orbit and investigate dwarf planet Ceres and Vesta. With mean radii of 470 km and 261 km respectively, they are the two largest and most massive objects in the main asteroid belt. Based on a main asteroid belt mass of $2.7 \cdot 10^{21}$ kg,[1] Ceres is 35% of the total and Vesta is 10%. These protoplanets are believed to retain records of the physical and chemical conditions from the epoch of planet formation.

At each destination, the spacecraft acquired panchromatic (in stereo) and narrowband images in the visible and near infrared; infrared, visible, gamma ray, and neutron spectra; and gravimetry.

Dawn is the only spacecraft to have orbited an object in the main asteroid belt, and it is the only spacecraft to have orbited *any* two extraterrestrial destinations. The mission is enabled by solar electric propulsion (SEP), implemented as an ion propulsion system (IPS). Without SEP, a mission to orbit either Vesta or Ceres alone would have been unaffordable within the National Aeronautics and Space Administration's (NASA's) Discovery Program. A mission to orbit both would have been impossible.

The project is managed by the Jet Propulsion Laboratory (JPL) which also conducts mission operations. The current principal investigator is at JPL (the original was at the University of California, Los Angeles).

Designing, building, testing, and launching the spacecraft was the responsibility of Orbital Sciences Corporation (now Northrop Grumman Innovation Systems). JPL delivered some subsystems and components to Orbital.

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The nuclear spectroscopy is accomplished with the gamma ray and neutron detector (GRaND). GRaND was delivered by the Los Alamos National Laboratory and is operated by the Planetary Science Institute.

Imaging (both for science and navigation) is accomplished with a prime and backup camera (framing camera 2, or FC2, and FC1, respectively). The two units were contributed to NASA by the Max-Planck-Institut für Sonnensystemforschung (Max Planck Institute for Solar System Research) with cooperation by the Institut für Planetenforschung (Institute for Planetary Research) of the Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center) and the Institut für Datentechnik und Kommunikationsnetze (Institute for Computer and Communication Network Engineering) of the Technischen Universität Braunschweig (Technical University of Braunschweig).

Visible and infrared mapping spectrometers are integrated into one package known as VIR. VIR was contributed to NASA by the Agenzia Spaziale Italiana (Italian Space Agency). It was designed, built, and tested at Galileo Avionica (now SELEX ES) and is operated by the Istituto di Astrofisica e Planetologia Spaziali (Institute for Space Astrophysics and Planetology).

The spacecraft and payload design, as well as the mission design and scientific objectives, have been presented elsewhere.[2,3]

Dawn launched on a Delta 7925H-9.5 on 27 September 2007. The interplanetary cruise phases as well as operations at Vesta in 2011–2012 and at Ceres since 2015 have been described in detail.[4-12]

The spacecraft entered orbit around Ceres on 6 March 2015 and operated in four circular orbits of progressively lower altitude. Having met or exceeded all of its original objectives, the prime mission concluded in June 2016. At that time, Dawn was in its circular low altitude mapping orbit (LAMO) at 385 km.

The first extended mission (XM1) began in July 2016. Dawn continued observing Ceres for another two months from that orbit, then designated extended mission orbit 1 (XMO1). Subsequently the orbital altitude was raised to pursue new scientific objectives.

The mission at Ceres through 4 September 2017 was described by Rayman.[12] One activity not described was an orbital maneuver to prepare for a second extended mission (XM2). We begin the new discussion of Ceres operations here with that.

PREPARATION FOR XM2

As XM1 drew to a close, two options for XM2 were considered. One was to continue to investigation Ceres and the other was to leave Ceres to fly by asteroid 145 Adeona in the second half of 2019.

Three of Dawn's reaction wheels had failed in 2010, 2012, and 2017. Attitude control for both mission options would be accomplished most of the time with the hydrazine-based reaction control system (RCS) and, during IPS thrusting, with the IPS engine for two axes and RCS for the third. Conservation of hydrazine had been a major effort of the mission since 2010. Still, it had not been expected to be so successful that a second extended mission would be feasible.

By the time Dawn had completed its XM1 objectives at high altitude, there was not enough hydrazine available to return to LAMO/XMO1 and operate long enough to acquire any new, valuable data. Instead, if the spacecraft stayed at Ceres, it would be maneuvered to a highly elliptical orbit with a peridemeter below 200 km, well below the 385-km altitude of LAMO/XMO1.

(Peridemeter is the term adopted for periapsis at Ceres. Demeter is the Greek counterpart of Ceres, the Roman goddess of agriculture.)

The other possible mission was to go to Adeona, a Ch asteroid with a mean diameter of 150 km. It is noteworthy that after being the only spacecraft to orbit two extraterrestrial targets, and even maneuvering extensively in orbit around Vesta and Ceres, Dawn had the capability to leave Ceres and reach a third destination. There was not enough xenon propellant remaining to orbit Adeona. Nevertheless, the encounter would have been at the unusually low velocity of < 1 km/s, enabling a rich scientific return.

XMO4 had been established for the unique opposition observation. About 14,000 × 53,000 km, the orbit had a period of 60 days. As NASA conducted a thorough review of the two mission options, the project recognized that both options would be improved by reducing the period. For staying at Ceres, that would put Dawn energetically closer to the low-peridemeter orbit. Departure opportunities for Adeona occurred at intervals of the XMO4 period. Reducing the period would provide more frequent opportunities. Although Dawn had the capability to reach Adeona with departures throughout 2016 and almost all of 2017, later departures yielded slightly higher encounter velocities. Enabling a slightly earlier departure, at the expense of a small amount of Xe to change the orbit, yielded a lower encounter velocity at Adeona and hence a better scientific return.

With three periods of ion thrusting from 3 June to 23 June 2017, totaling 257 hours, Dawn maneuvered from XMO4 to XMO5, which had a period of 30 days. The 5400 × 38,000 km orbit was aligned to provide optimal performance for a mission to Adeona. (The alignment was unimportant for staying at Ceres.)

Dawn was in solar conjunction during much of the thrusting. When thrusting commenced, the Sun-Earth-probe angle was less than 2°, and it reached as low as 0.7°. As Dawn had already thrust for 59% of its time in space, thrusting was the default state of the spacecraft. It was reliable enough that there were no concerns about thrusting during conjunction.

In October 2017, NASA approved XM2 for further orbital exploration of Ceres. Even with the extensive data Dawn had already acquired, the dwarf planet was too interesting to leave even in exchange for a slow flyby of Adeona.

Even as NASA was assessing the XM2 proposals, the flight team had already begun detailed trades and investigations of how to maneuver to and operate in highly elliptical orbits with low peridemeters to accomplish new measurements. Because of Ceres' water, organics, other chemicals, and internal heat, planetary protection required that the spacecraft not contact it for at least 20 years. In addition, analyses were needed for how to maneuver to such orbits, how to achieve adequate orbit knowledge and control, and possible environmental effects on the spacecraft from going closer to the dwarf planet. Moreover, new concepts for science data acquisition and spacecraft operations were needed. For all studies, hydrazine consumption was a crucial metric to ensure operations would last long enough to be productive. As planned, after approval for XM2, six more months of work was needed before Dawn would be ready to go to a lower orbit.

While Dawn was in XMO5, it continued the measurement of the cosmic ray background with GRaND that it had begun in XM1. These data proved valuable in reducing the noise in the nuclear spectra acquired in LAMO/XMO1. (This had been determined to be a better way to improve the signal-to-noise ratio than increasing the signal in the hydrazine-expensive XMO1.) In addition, Dawn undertook a campaign to compare GRaND observations of solar energetic particles (SEP) with measurements by other instruments nearer Earth. Telescopic observations of Ceres were planned as well to test the finding that SEP impingement on Ceres might create a transient water vapor atmosphere. With an unusually quiet Sun, no significant SEP events were observed.

XMO6

The prime objective of XM2 was to reach an orbit with a peridemeter below 200 km. However, there were other valuable objectives for altitudes above that. During the prime mission and XM1, Dawn had fully mapped Ceres with its camera, in color and in stereo, from the 1,470-km third science orbit (known as the high altitude mapping orbit, or HAMO) and mapped it again in LAMO/XMO1, with color and stereo in selected areas. However, even with additional VIR observations in XMO2, at an altitude close to HAMO's, VIR had not observed as much of Ceres because of its smaller field of view, higher data volume per unit surface area, and tighter constraints on surface illumination. The Sun had been in Ceres' northern hemisphere for all of the observations from the beginning of the mission through the end of XMO2, so coverage was more extensive in the northern hemisphere than the southern.

From the planned, low-peridemeter orbit (XMO7), extensive new coverage would not be possible. Therefore, an intermediate orbit was designed to accomplish VIR objectives.

XMO6 initially was designed as an extended forced-coast period in the optimal transfer from XMO5 to XMO7. Small adjustments to the transfer allowed XMO6 to be improved to meet specific VIR observation requirements without adding significant time to the transfer.

Southern solstice was on 23 December 2017. Even with an obliquity of only 4°, illumination in the southern hemisphere during XM2 was better than it had been during the prime mission and XM1. The VIR observations of greatest interest were between 50°S and 75°S, so XMO6 was designed to optimize acquisition of infrared spectra in that range.

Ceres' perihelion of 2.56 AU occurred on 28 April 2018. XMO6 also presented an opportunity to compare the surface with what had been observed at other times, including at the 2.98 AU aphelion on 6 January 2016.

XMO6 provided the opportunity for other observations as well. A target of special interest was Juling Crater (Fig. 1). With infrared observations spanning six months in 2016, including targeted observations in XMO2 at three different local solar times, the area of ice on Juling's north wall was seen to increase from 3.6 km^2 to 5.5 km^2.[15] The change is attributed to seasonal changes in insolation. Juling is at 36°S. As the Sun moved south during that time, the floor of the crater experienced more heating and thus released more water vapor. The colder, shadowed north wall acted as a cold trap. Acquiring spectra of Juling again in XMO6 was thus of interest, and that objective constrained the ground track and timing of the orbit. Targeting of XMO6 accounted for the predicted perturbative effects of RCS activity during the orbits that preceded the planned Juling observation.

The transfer from XMO5 to XMO6 (shown in Fig. 2) started on 16 April 2018. After 631 hours of ion thrusting and 121 m/s, ion thrusting concluded on 14 May. The 450 km × 4730 km orbit had a period of 37 hours.

Science observations were conducted in the 10 orbits from 16 May to 30 May, generally for ~ 6 hours per orbit. In addition to VIR mapping in the southern hemisphere and the targeted observation of Juling, FC and VIR observed other areas as well, including in the northern hemisphere. Most observations were at nadir, but selected off-nadir attitudes were used to observe targets of particular interest.

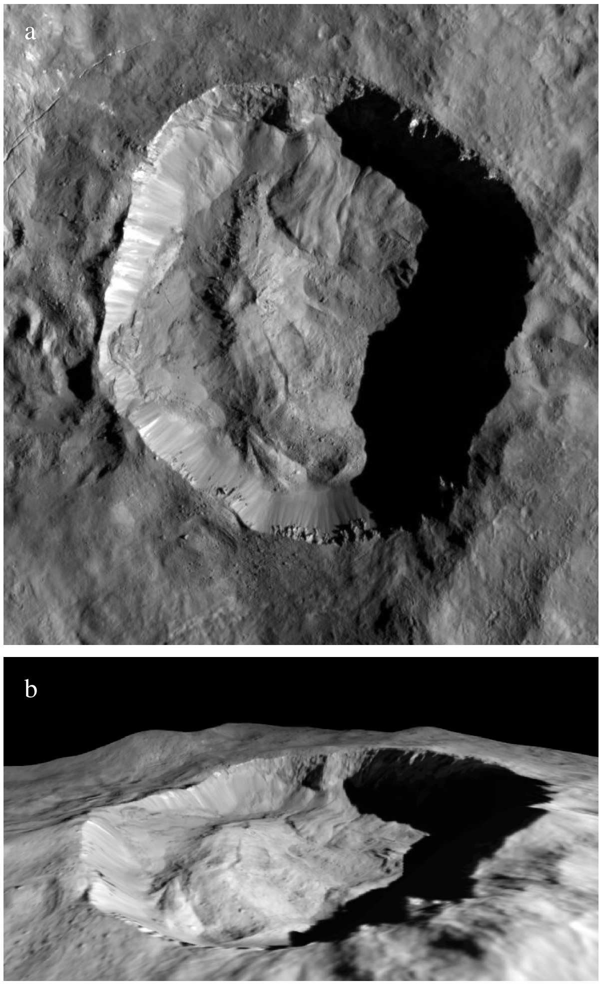

Figure 1. Juling Crater. The crater is 20 kilometers in diameter. (a) This image was acquired in XMO1. (b) This perspective was synthesized with multiple images acquired in LAMO/XMO1.

XMO6 was designed to provide an off-nadir angle for the Juling observation to optimize the view of the crater's north wall. It was placed near the middle of the XMO6 phase to allow time to refine the orbit knowledge after the transfer was complete.

The hydrazine cost of turning between pointing the instruments at Ceres and pointing the high gain antenna at Earth was managed carefully. The spacecraft only turned to downlink data on six of the orbits. The long orbit period with much of the time over the nightside of Ceres provided sufficient time to downlink the stored data. On the other orbits, to save hydrazine, Dawn continued pointing at Ceres even when there were no useful data to acquire because of altitude and illumination.

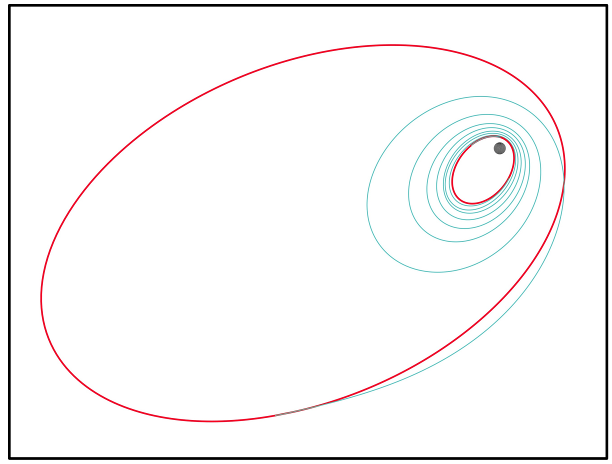

Figure 2. Transfer from XMO5 to XMO6. The two science orbits are shown in red, and the transfer trajectory is in blue.

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For the great majority of the mission, Dawn operated no more than one FC at a time to ensure faults would not damage both. FC2 was the preferred unit. FC1 was kept as a cold spare, generally operated twice each year to verify its health and calibrate it. The two cameras were operated simultaneously for the first time in 2017 in XMO3 and then again in XMO4. Both cameras were used for the majority of XMO6, reducing vulnerabilities to rare instances in which FC2's computer resets and prevents acquisition of data. No resets occurred in XMO6, and together the two cameras provided more than 1,800 images.

On three orbits when there was data volume to spare, following the completion of science observations and before turning to point the high-gain antenna (HGA) at Earth, the spacecraft turned to point the cameras at Ceres' limb. The direction of the turn was chosen to minimize the hydrazine cost. Imaging continued from nadir to the limb, yielding not only new images for topography (which had been a significant part of HAMO and XMO1) but also appealing views of the limb. Examples are in Fig. 3

Despite significant uncertainties in predicting the ground track, principally from errors in predictions of RCS-induced perturbations during the transfer to and operation in XMO6, all measurement objectives were met. In addition to the images with FC1 and FC2, Dawn acquired 2.3 million infrared spectra with VIR.

XMO7

XMO7 is the final orbit for the entire mission. Dawn was recognized to be so low on hydrazine, and the rate of use would be so high in XMO7, that the project could not count of further orbit changes. Moreover, the orbit was intended to have a sufficiently low peridemeter that as long as Dawn could operate there, valuable new data could be acquired.

The primary objective of XMO7 was to reach a low enough altitude to make significant improvements in both spatial resolution and sensitivity of nuclear spectroscopy. The lowest feasible peridemeter would yield the best science. Improvements in spatial resolution of gravity measurements, imaging, and infrared and visible spectroscopy were of great interest as well.

Trade studies considered orbits with peridemeters as high as 200 km and as low as 30 km. The lowest peridemeter was attractive for all investigations, but the peridemeter chosen was 35 km to increase margin for the planetary protection requirement of no impact within 20 years. See Fig. 4.

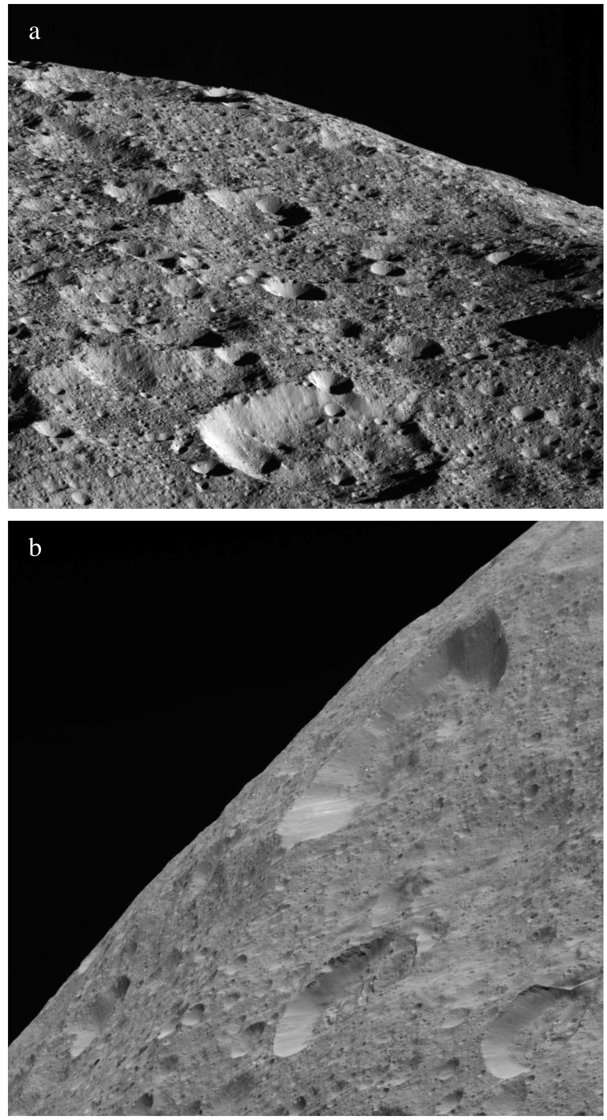

Figure 3. XMO6 limb views. Image (a) was acquired on 16 May. The limb is about 800 km away. The large crafter in the foreground is 27 km in diameter. The crater seen nearly edge-on on the limb at upper left is 120 km away from it and is 31 km in diameter. Image (b) was acquired on 30 May. The limb is about 730 km away. The largest crater is 35 km in diameter. The distance from the lower right corner of the picture to the limb is about 165 km.

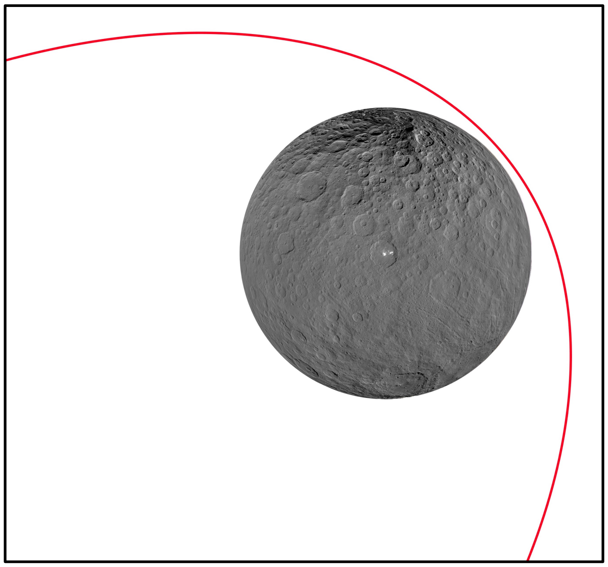

Figure 4. XMO7 peridemeter. The peridemeter altitude is 35 km, compared to Ceres' mean radius of 470 km. Dawn revolves counterclockwise in this perspective, traveling north at low altitude on the dayside. Velocity at peridemeter is 0.47 km/s. Dawn spends about 1.25 hours below 385 km, which was the previous lowest altitude (in LAMO/XMO1). The XMO7 peridemeter altitude is 9% of the LAMO/XMO1 altitude. Fig. 6 illustrates the entire orbit. Dawn acquired this image of Ceres as part of the opposition observation in XMO4. Note Occator Crater at the center, with its reflective deposits of salt (shown in greater detail in Fig. 5).

The planetary protection analysis was based on Monte Carlo studies that included the best 18 × 18 gravity field with conservative uncertainties and RCS activity during operations. The 35-km peridemeter had no impacts in 1,150 samples propagated for 20 years. Additional studies provide > 99% confidence of an orbital lifetime of 50 years.

The selection of apodemeter involved many issues. A high apodemeter would reduce the time needed for the orbit transfer. In addition, for nuclear spectroscopy, it was desirable to have an apodemeter high enough that GRaND could measure the cosmic ray background on each orbit. However, a higher apodemeter translated into greater velocity at peridemeter, thus complicating science data acquisition, increasing the hydrazine cost of pointing the instruments, and increasing FC and VIR smear. Moreover, longer orbit periods yield a lower duty cycle for science data acquisition, an important consideration given the limited time before hydrazine would be exhausted.

Ceres' gravity field causes the latitude of peridemeter to shift south with each orbit. That would be valuable for the investigation of the depth of ice as a function of latitude. GRaND had previously demonstrated that ice is shallower at higher latitudes.

An area of special interest for high resolution observations with all instruments was the 92-km-diameter Occator Crater.[12-14] At the center is Cerealia Facula, the largest deposit of sodium carbonates known in the solar system except on Earth. Briny water that froze and sublimated left the dissolved salts behind, forming the brightest feature on Ceres, ~ 10 km in diameter. In the eastern part of the crater is a more diffuse but still prominent deposit (Vinalia Faculae). These presented scientifically attractive targets. (See Fig. 5.)

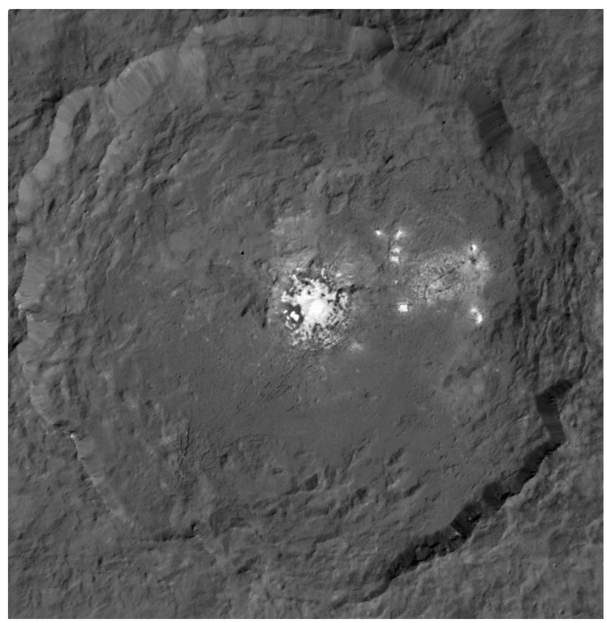

Figure 5. Occator Crater. Cerealia Facula is in the center of the 92-km-diameter crater, and the other reflective areas are collectively denominated Vinalia Faculae. This is a combination of two images acquired in HAMO at an altitude of 1,470 km, one with an integration time for typical Ceres scenes and one with a short integration time for the faculae. Figs. 9-14 show some details of the crater.

Uncertainty in the extensive RCS activity near peridemeter made orbit prediction uncertainties significant. With standard procedures, the probability of acquiring images and spectra of specific targets was low. Credible timing uncertainties of a few minutes at the time of sequence development (weeks before execution) meant Ceres' rotation could move features by distances large compared to the FC and VIR fields of view.

Occator is at 20°N latitude. With an apodemeter chosen to provide a 3:1 synchronous orbit with Ceres' rotation (generally called a resonant orbit by the Dawn project), Dawn would have multiple opportunities to observe Occator at very low altitude before peridemeter shifted too far south. Therefore, an orbit period of 27 hours was chosen, dictating an apodemeter of 4,000 km given the peridemeter of 35 km. The longitude of peridemeter was at Occator's longitude. Fig. 6 illustrates XMO7.

The transfer to XMO7 began on 31 May. After 132 hours of ion thrusting and 26 m/s, ion thrusting concluded on 6 June. The transfer is shown in Fig. 7.

Science data acquisition with all instruments began on 9 June. As in XMO6, the cameras were used simultaneously. Each peridemeter had a unique ground track, and so near the end of the mission, the reduction in risk of a camera reset that prevented imaging outweighed the small increase in risk of simultaneous operation. Moreover, even at the fastest rate of one image every seven seconds, it was not guaranteed that images from one camera would overlap, given the 95-mrad field of view. Therefore, the timing of the two cameras was offset to minimize gaps.

In most cases early in XMO7, Dawn downlinked data after every other peridemeter, conserving hydrazine in some orbits by not turning to point the HGA at Earth.

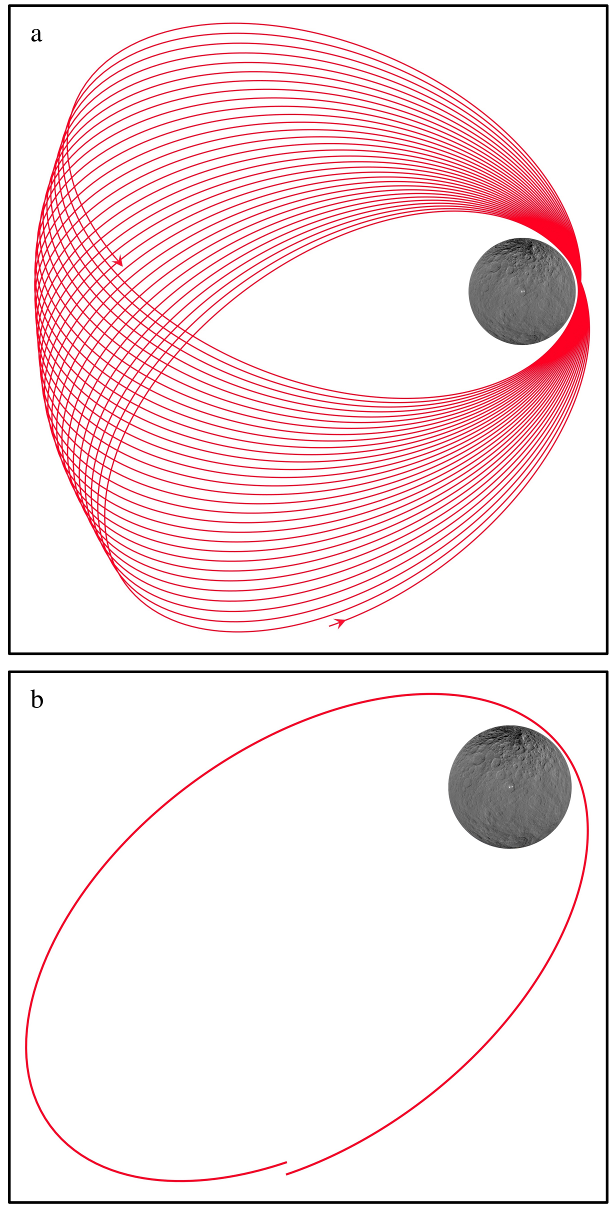

Figure 6. XMO7. As in Fig. 4, Dawn revolves counterclockwise in these illustrations. The peridemeter's 1.9° southward shift with each revolution is shown in (a). One revolution is isolated in (b) for clarity.

The initial latitude of peridemeter was chosen so the latitude of peridemeter would be nearest Cerealia Facula on 23 June and 24 June. That provided sufficient time to characterize the behavior of the orbit to target observations.

Windows had been built into the plan for a pair of trajectory correction maneuvers (TCMs) in preparation for the Cerealia Facula observations. During ion thrusting, the attitude is determined by the time-dependent thrust vector, which would not be compatible with pointing instruments at Ceres. Each peridemeter was so scientifically valuable that the TCM windows were scheduled not to interfere.

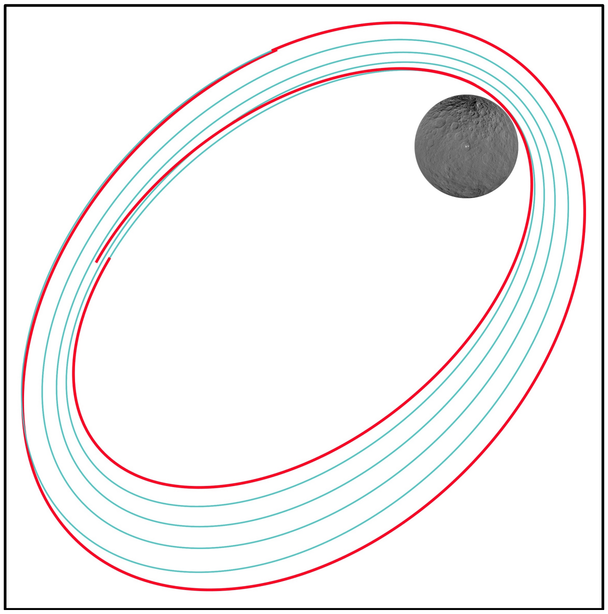

Figure 7. Transfer from XMO6 to XMO7.

On 21 June, Dawn thrust for 127 minutes and then 15 hours later for 71 minutes. The combined 0.55 m/s adjusted the orbit to bring the flight path over Cerealia Facula on 23 and 24 June.

The TCM was the last planned use of the IPS for the entire mission. The orbit remains compliant with planetary protection requirements and the ground track is sufficient to yield excellent science opportunities for as long as the hydrazine lasts.

All post-launch trajectory control was accomplished with the IPS, apart from a gravity assist at Mars. The IPS provided 11.5 km/s over its 51,385 hours of accumulated thrust time. Uninterrupted thrust periods ranged in duration from 11 minutes for a statistical maneuver in orbit around Vesta to 31.2 days during the interplanetary cruise from Vesta to Ceres.

The TCM executed correctly. Nevertheless, uncertainty in orbit perturbations induced by RCS activity were too large for the normal schedule of updating the onboard data needed for pointing.

The project developed a streamlined procedure that allowed for a rapid update. Data acquisition for the 22 June peridemeter began three hours after the thrusting completed. Following three hours of normal peridemeter science observations, Dawn turned to point its HGA to Earth.

Downlink with the HGA provided three data types of value for the update to the pointing: radiometric tracking, telemetry on RCS activity (used in fitting the orbit), and images.

Dawn was so much closer to the ground in XMO7 than it had been in LAMO/XMO1, even the uncertainty in the location of Cerealia Facula itself was not negligible. There was not enough time for an optical navigation solution to be incorporated into the orbit prediction, but rapid visual inspection of the images revealed part of Cerealia Facula (and showed exciting details, as seen in Fig. 10), thus helping to establish the ground track relative to the target.

All prior peridemeter observations pointed the instruments to nadir (with nadir determined by the onboard ephemeris). On 22 June, a new ephemeris was developed for uplink to the spacecraft. The operating sequence had been built to allow a late change in the pointing relative to nadir for the two subsequent peridemeters. When it was determined to be probable that Dawn would not fly directly over Cerealia Facula, new commands with the appropriate angular offsets were developed and uplinked.

The quick update was successful, yielding high resolution data on the two targeted peridemeters as well as the one between the TCM and the targeted orbits.

Following the campaign to observe Cerealia Facula, operations transitioned to a different cadence. To reduce hydrazine use, Dawn acquired and stored data on five consecutive peridemeters. Following the fifth, it turned to Earth and downlinked data for nearly two full revolutions, ending in time to turn again for peridemeter. That meant that for one peridemeter in every six, instruments would not be pointed at nadir. Keeping the HGA on Earth through peridemeter improved the radiometric data for gravity science compared to using a low gain antenna. More importantly, using less hydrazine extended the duration of XMO7, providing opportunities to acquire high resolution data farther south as the latitude of peridemeter continued to move.

Even with RCS forces, the orbit period remained sufficiently close to the desired 3:1 resonance that Dawn continued to pass over or very near Occator on every orbit. Small shifts east or west allowed greater coverage within the crater. In addition, more opportunities to point off-nadir were built in and used to gain additional data on Cerealia Facula.

By 12 August, the peridemeter had shifted so far south that Dawn was at LAMO/XMO1 altitude when it was as far north as Occator. Prior to reaching XMO7, the project had considered investigating additional maneuvers after acquiring high-resolution data at Occator to shift the longitude to some other geologically interesting site farther south. However, it was quickly realized that the ground track would put peridemeter in Urvara Crater, 65° south of Occator.

Urvara (Fig. 8) was so valuable for high-resolution study that maneuvers to other sites were not needed. Occator Crater may be ~ 20 million years old. The 170-km-diameter Urvara is much older, providing an opportunity for comparison of relatively young and relatively old materials.

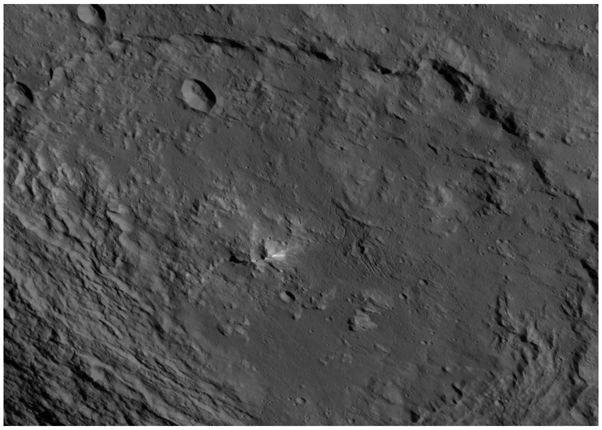

Figure 8. Urvara Crater. Dawn acquired this image in HAMO at an altitude of 1,470 km. Urvara does not have a central peak but rather a central ridge. Note the fracturing on the crater floor east of the center. Details in the crater are shown in Figs. 15-16.

By 12 August, Dawn had returned more than 2 million infrared spectra, nearly 49,000 visible spectra, and more than 8,000 images in XMO7.

Dawn's peridemeter will continue to move south until 26 August when it reach 84°S, corresponding to the orbital inclination. By early September, lighting will preclude imaging or reflectance spectroscopy below LAMO/XMO1 altitude. Nevertheless, if enough hydrazine remains for operations to continue, high resolution nuclear spectroscopy and gravity measurements will continue.

END OF MISSION

The end date of operations is uncertain because of the uncertainties in the amount of hydrazine onboard, the amount that is unusable, and the rate of use. As of early August 2018, the most probable exhaustion date is between mid-September and mid-October, but earlier and later dates are quite credible.

Unlike some spacecraft, Dawn is not expected to show specific evidence of the hydrazine nearing depletion. Rather, it will operate normally until an RCS thruster is commanded to fire and there is insufficient hydrazine available. The spacecraft will then lose attitude control.

With reasonable attitude rates, the time-averaged power from the solar arrays will not be enough to charge the battery. The downlink will be off.

The depletion will be inferred from the failure to observe the spacecraft with the Deep Space Network.

CERES XM2 HIGHLIGHTS

XM2 data are too new for new, meaningful conclusions to have been reached about Ceres. The improvement in spatial resolution from LAMO/XMO1 at 385 km to XMO7 peridemeter at 35 km is the largest of the mission at Vesta or Ceres. Therefore, we present in Figs. 9-16 a selection of the high-resolution images taken with the 93-μrad/pixel cameras and wait for further analyses before offering any interpretations or new conclusions about Ceres. Zoom in on the PDF to see more detail. All data will be available in the Planetary Data System, and in the short term, these and other images are available at http://dawn.jpl.nasa.gov.

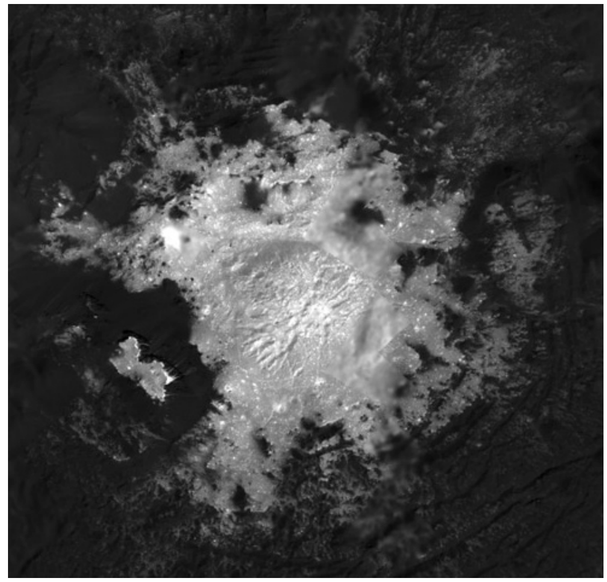

Figure 9. Cerealia Facula. This mosaic was constructed with images from multiple orbits in XMO7. The lowest images were taken from an altitude of 34 km. Integration times were optimized for the bright material. Gaps in XMO7 coverage are filled in with LAMO data. (Later images in XMO7 filled most of the gaps from an altitude well below LAMO.) The isolated bright structure on the left is shown in Fig. 10.

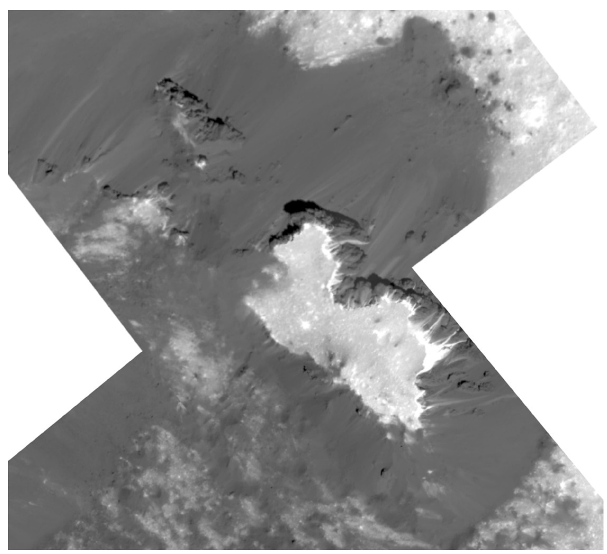

Figure 10. Detail of Cerealia Facula. The main bright structure here is visible on the left of Fig. 9. It is about 1.5 km in its longest dimension. It is located on a slope that goes down to the upper right of the picture. The two images of this mosaic were taken at an altitude of 34 km on 22 June in the first peridemeter after the TCM. As in the other images of the faculae, note the sharp boundaries between the bright material and the dark material.

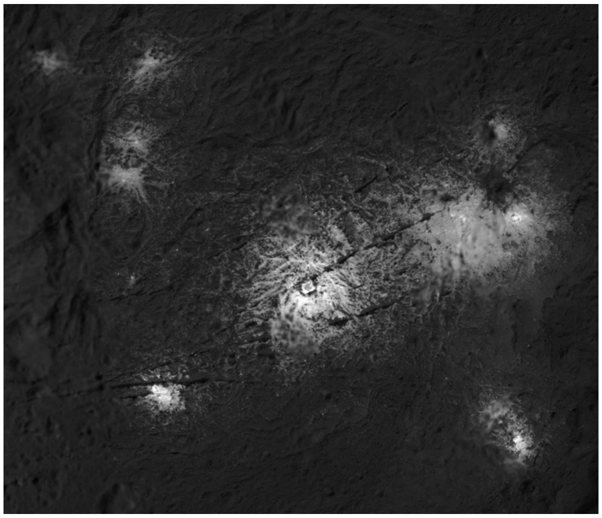

Figure 11. Vinalia Faculae. As in Fig. 10, this mosaic was constructed with images from multiple orbits in XMO7. The lowest images were taken from an altitude of 34 km. Integration times were optimized for the bright material. Gaps in XMO7 coverage are filled in with LAMO data. (Later images in XMO7 filled most of the gaps from an altitude well below LAMO.) Details of the nearly square structure near the center are in Fig. 12.

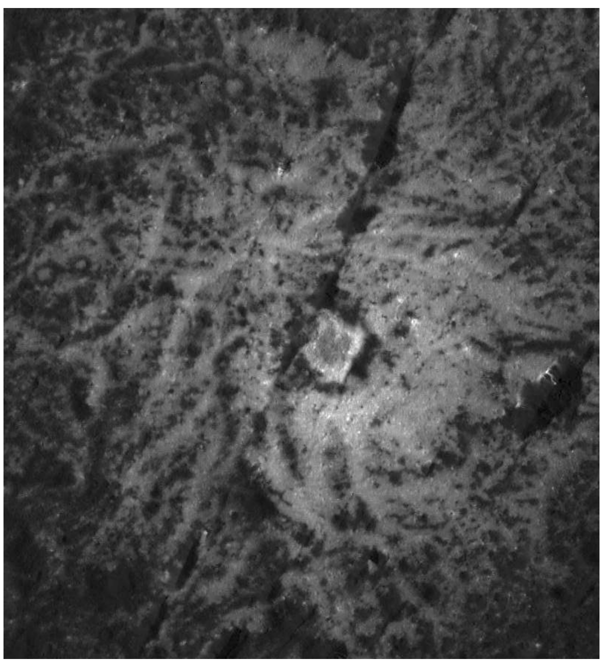

Figure 12. Vinalia Faculae detail. This image was acquired from an altitude of 58 km and shows an area near the center of Fig. 11 (but rotated here about 40° counterclockwise). The scene is 4.3 km wide. The integration time was optimized for the bright material. Note the intriguing bright curve on the right side of the picture, almost halfway up. Its shape suggests some kind of flow.

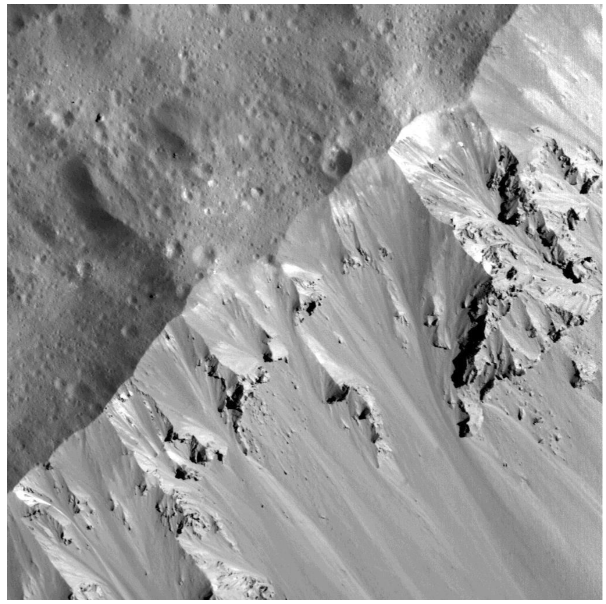

Figure 13. North wall of Occator Crater. This image was acquired from an altitude of 33 km and is about 3 km across. Note the many boulders that slid part way down the wall before stopping. Ceres' surface gravity is about 0.027g.

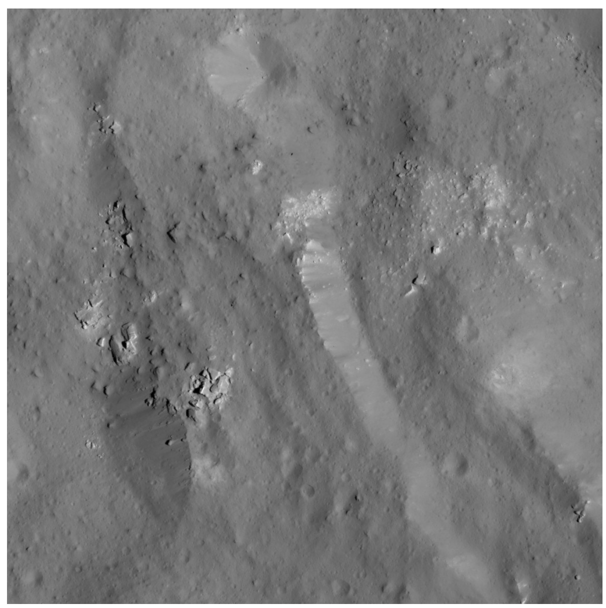

Figure 14. Boulder field in Occator Crater. This image inside Occator's eastern rim was acquired from an altitude of 48 km and is about 4.6 km across.

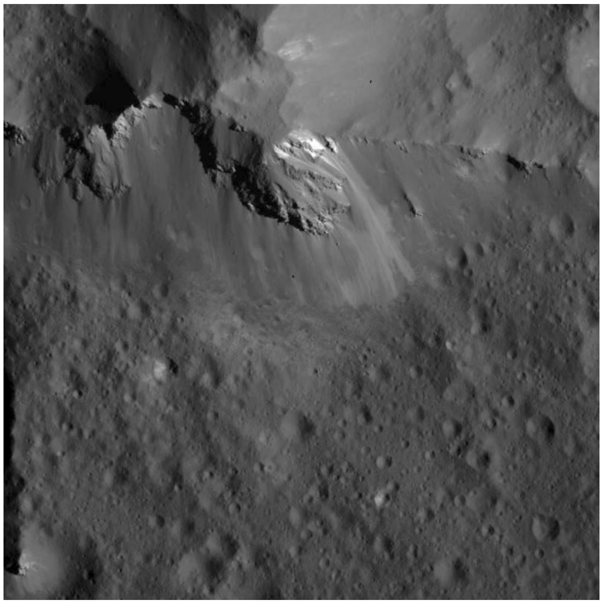

Figure 15. Ridge in Urvara Crater. This image of the central ridge was acquired from an altitude of 116 km and is about 8.6 km across. Note the patterns of bright material that apparently flowed downhill.

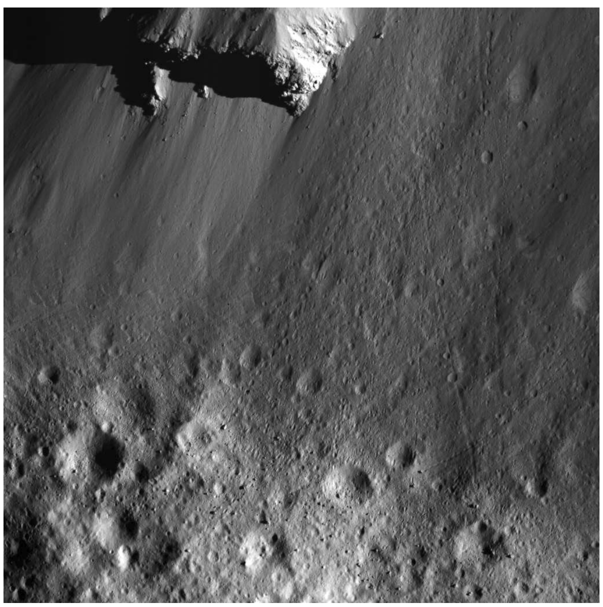

Figure 16. North wall of Urvara. This image was acquired from an altitude of 45 km and is about 4.3 km across. Boulders, and the trails they left as they fell down the wall, are visible.

CONCLUSION

After almost 11 years of flight operations, including 14 months in orbit around Vesta and 3.4 years (so far) in orbit around Ceres, Dawn's mission is nearly complete. Despite being designed to use three reaction wheels (and carrying four), Dawn has used only two or zero for more than half of its operational life. (There is no one-wheel mode.) Despite this and other challenges, Dawn has explored about 45% of the mass contained in the main asteroid belt and is now completing an extremely productive second extended mission, providing unique and valuable Ceres data.

The spacecraft will deplete its hydrazine very soon (perhaps even before the IAC at which this paper is presented), concluding mission operations. The orbital lifetime will be > 20 years (and, with high confidence, > 50 years), satisfying planetary protection requirements.

Upon expending the last of the hydrazine, the spacecraft will no longer be capable of operations and will be uncommunicative. Dawn will become an inert celestial monument to human creativity, ingenuity, and curiosity, a lasting reminder in orbit around the dwarf planet it unveiled that our passion for bold adventures and our noble aspirations to extend our reach into the universe can take us very, very far beyond the confines of our humble planetary home.

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